

The Future



of

Fundamental Physics



Nima Arkani-Hamed  
Harvard University

# Theoretical Physics

Thrives on

CRISES +  
PARADOXES.

Many of us feel that  
our current struggles are  
paving the way...

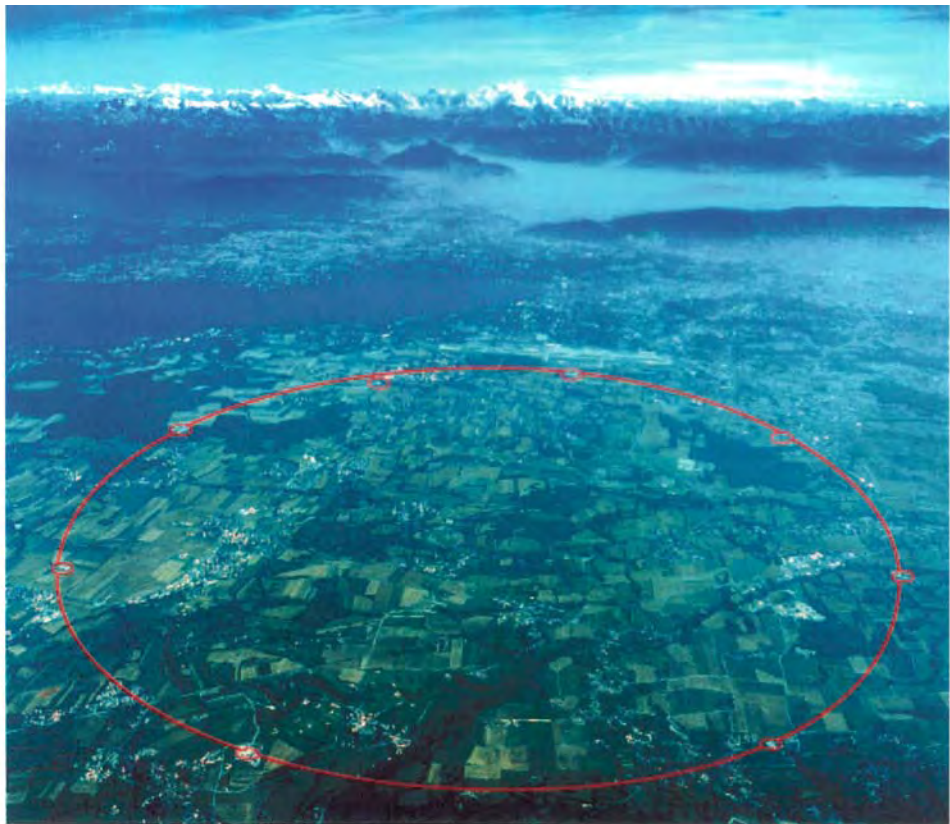
... for a Revolution  
in our understanding  
of physics on the same  
scale as those of  
Relativity + Quantum Mechanics  
at the beginning of the  
20<sup>th</sup> century.

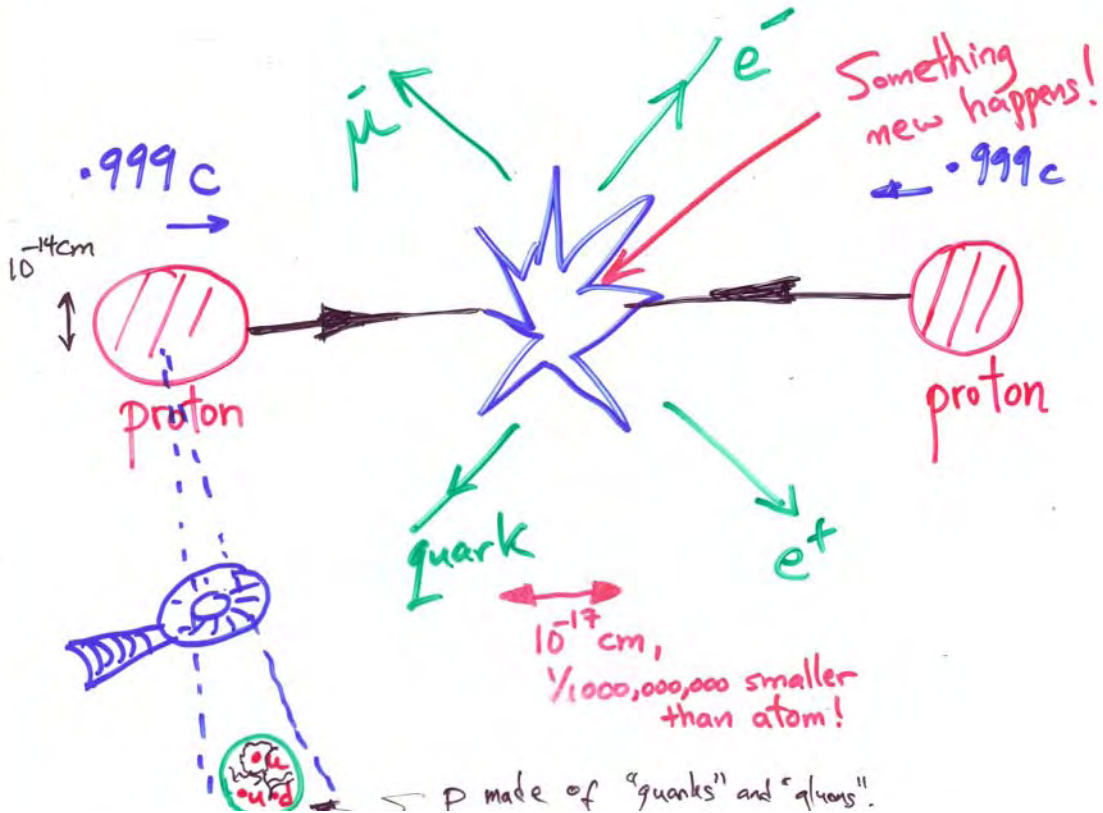
A spectacular new  
EXPERIMENT -  
the Large Hadron Collider  
might well usher in  
the revolution.

Begins Operation  
NEXT YEAR!

A spectacular new  
EXPERIMENT -  
the Large Hadron Collider  
might well usher in  
the revolution.

Begins Operation  
NEXT YEAR!









# 4 Basic Interactions

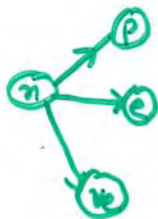
Gravity



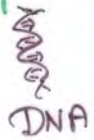
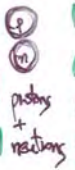
Electromagnetism



Weak + Strong




$10^{-17}$  cm  
"Weak"  
length




$10^{28}$  cm  
Size of  
Universe

$10^{-17}$  cm  
"Weak"  
length

  
p  
n  
protons  
+  
neutrons

  
Atom

  
people

  
DNA

L.H.C.

  
Solar  
system

  
Galaxies

  
 $10^{28}$  cm  
Size of  
Universe



$10^{-33}$  cm  
"Planck  
Length"



$10^{-17}$  cm  
"Weak"  
length



$10^{+28}$  cm  
Size  
of Univ.



$10^{-33}$  cm  
"Planck Length"



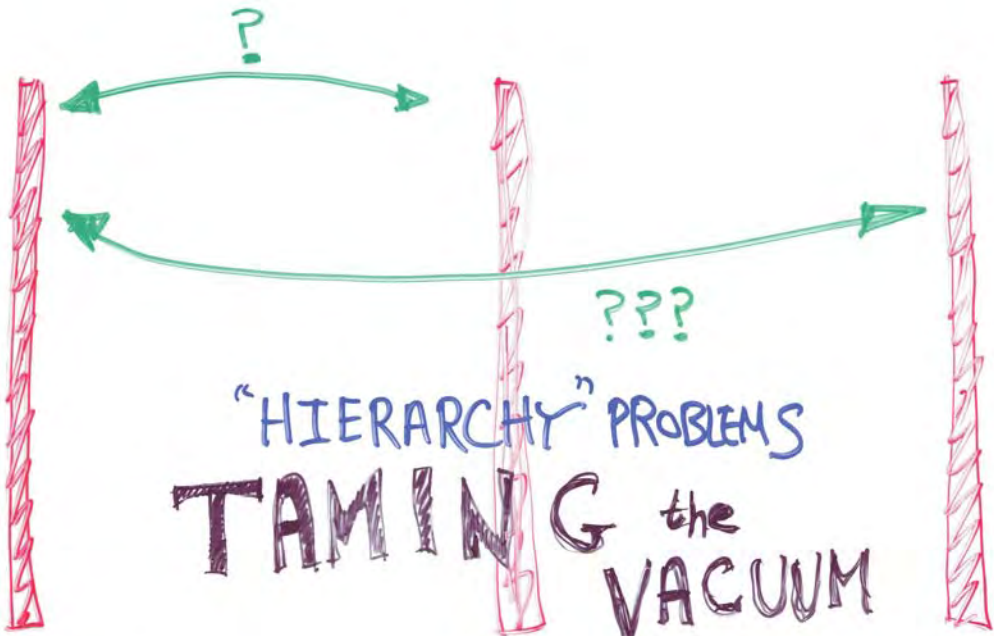
- Quantum Gravity
- EMERGENT SPACETIME
- String Theory + BEYOND



$10^{-17}$  cm  
"Weak" length



$10^{28}$  cm  
Size of Univ.



"HIERARCHY" PROBLEMS  
TAMING the VACUUM

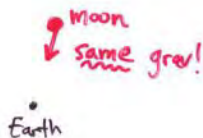
$10^{-33}$  cm  
"Planck Length"

$10^{17}$  cm  
"Weak" length

$10^{28}$  cm  
Size of Univ.

- How did we get here?
- Where might we go?
- What could the L.H.C. teach us?

# Unification



different aspects of same thing!



1900 - 1930 brought more  
profound insights:

Special + General Relativity

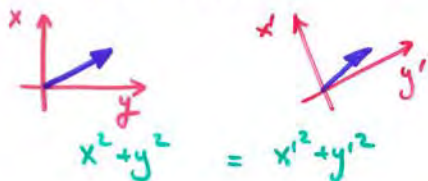
and the even more  
radical

Quantum Mechanics

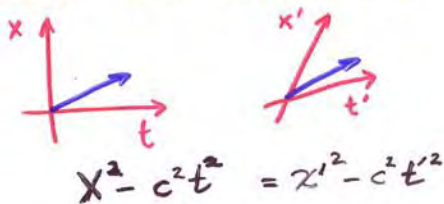
S. R.

## Space + Time Unified

... Just as spatial directions can be rotated into each other ...



... So can time + space be "rotated" into each other



# Energy + Mass Unified

$$E = M c^2$$

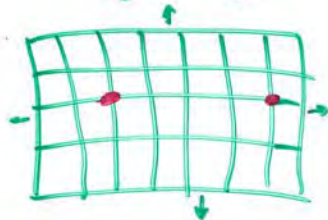
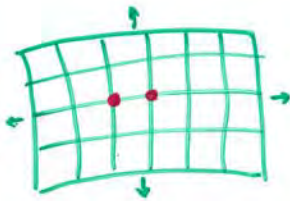
---

G.R.

Earth follows "shortest" path!



Spacetime  
becomes curved,  
= gravity

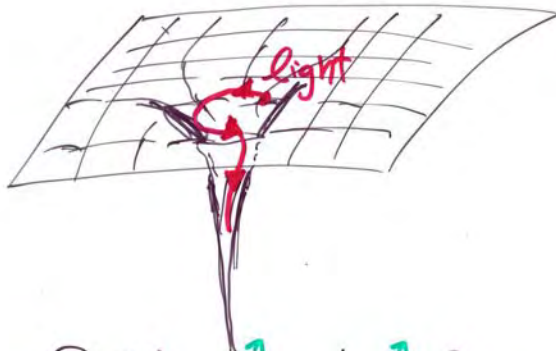


Expanding Universe

# Black Hole



even light  
can't escape



$$\frac{GM}{R} m = \frac{1}{2} m c^2$$

# Quantum Mechanics

Waves  $\leftrightarrow$  Particles

In fact no waves, but

Quantum Particles

Sometimes  
behave as  
classical  
waves

Failure of  
classical Determinism

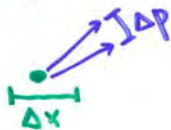
Sometimes  
like  
classical  
particles

Uncertainty Principles

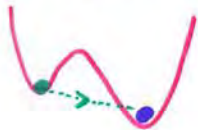
$$\Delta X \Delta p \sim h$$

$$\Delta E \Delta t \sim h$$

Planck's Constant



- Allows bizarre new phenomena  
e.g. "tunneling"



[Basis for much  
of our technology  
today!!!!]

- Ironically, uncertainty  $\Rightarrow$   
stability of atoms + matter.



$e^-$  can't  
"fall" into  
nucleus  
due to  
uncert. principle!

Synthesis of Special Rel.

+ Quantum Mechanics

= "Quantum Field Theory"

↳ Forces + predicts the  
existence of anti particles!

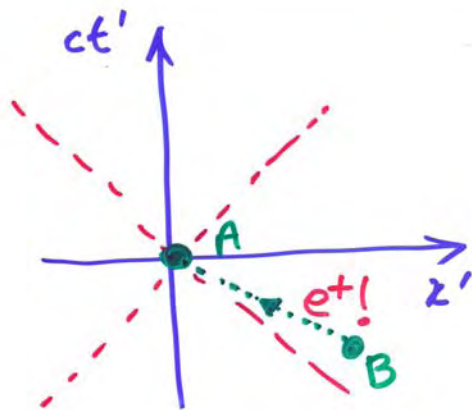
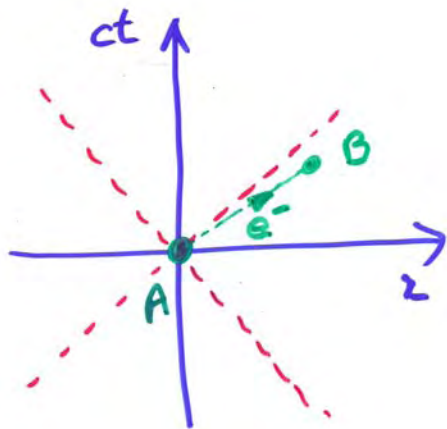
$e^-$

$e^+$

$p^+$

$p^-$

} Amazing: Unif.  
of Space-time  
+ QM doubled  
the world!





# Fundamental Change to notion of "vacuum"



Resolving  
 $\Delta t$  needs ; if  
 $\Delta E \sim \hbar / \Delta t$   $\Delta E > 2m_e c^2$   
 "see"  $e^+ e^-$  pair.

GR made spacetime  
dynamical ;

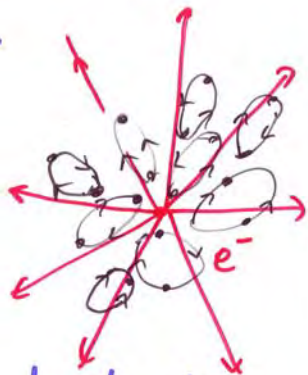
QM + SR make  
vacuum dynamical



... This resolved an old  
classical mystery:



Infinite  
energy  
of point  
electron



due to  $e^+e^-$   
cloud,  $e^-$  becomes  
effectively "fuzzy"  
at distances  
smaller than  
 $(h/mec)$ .

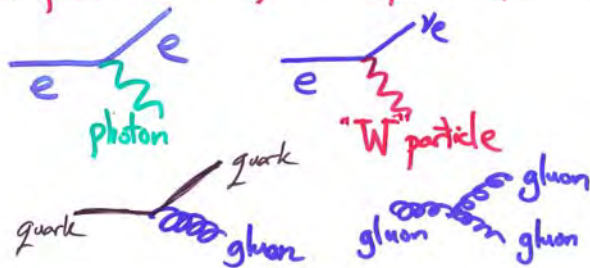
These developments culminated  
in the 1970's - into  
a theory known as the

"Standard Model" of all  
interactions. Spectacularly  
successful at describing everything  
at distances  $\geq 10^{-16}$  cm.

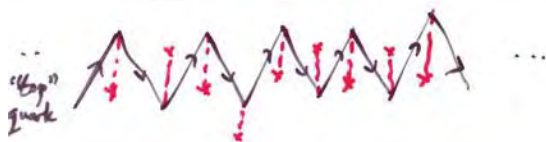
NO EXPERIMENT contradicts  
it - even @ precisions approaching  
 $1/1000$  (hundred measurements) and even  $10^{-12}$ !

The huge apparent disparity  
between electromagnetism,  
strong + weak interactions is  
a long-distance illusion:

around  $10^{-16}$  cm, they are very  
similar - Standard Model gives  
unified description of all of them:



# Origin of Mass



Typical length scale between int  
 $\sim 10^{-17}$  cm;  $\Rightarrow$  L.H.C. is  
guaranteed to excite  
Higgs "particle". Evidence  
by 2010

---

So What  
are  
the Crises?

# Emergent Spacetime



But when  $\frac{G_N \Delta E}{c \Delta t} \sim c^2$ , little region turns into Black Hole!

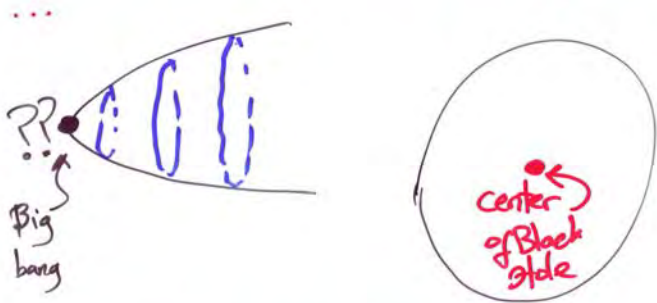
$$\Delta t^2 \sim \frac{G_N \hbar}{c^3} \sim t_{\text{pl}}^2, \quad t_{\text{pl}} \sim 10^{-43} \text{ s.}$$
$$l_{\text{pl}} \sim 10^{-33} \text{ cm.}$$

No operational meaning to smaller spacetime separations. Very High Energy  $\leftrightarrow$  LONG

distances! SPACETIME IS  
DOOMED. Must approximate something

REMOVED

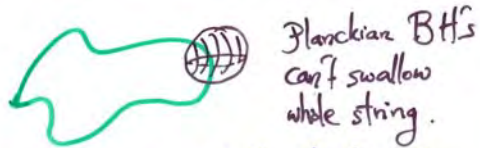
These issues also become important



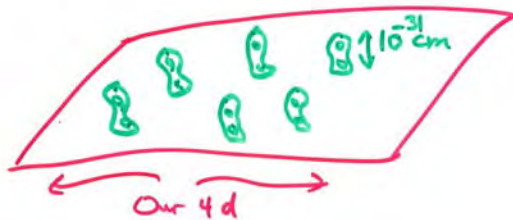
Our theories simply  
break down when gravity  
+ QM both become important.



# String theory pre '95



10 dimensions  $\rightarrow$  6 "curled up"  
to 4:



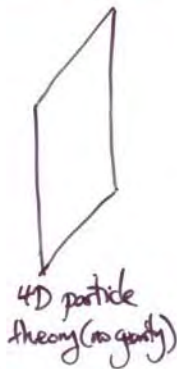
# Strings post '95

- Not a theory of strings!

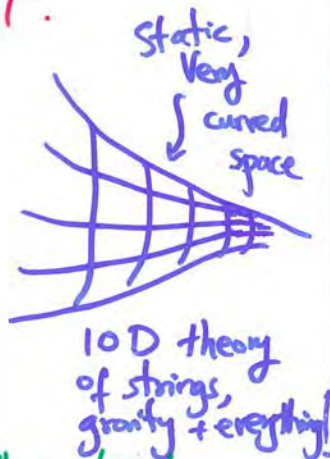


- Strings + extra dimensions can have any size.
- Particle  $\leftrightarrow$  String unification  
(best understanding of String theory is in terms of a particle theory!) via..

.. the incredible idea of  
HOLOGRAPHY.



=



- Most important theoretical discovery of last 20 years.
- EMERGENT SPACE,  
at least in some examples.

A more disturbing realization:

string theory is "unique": no adjustable parameters. BUT, it has zillions of solutions.

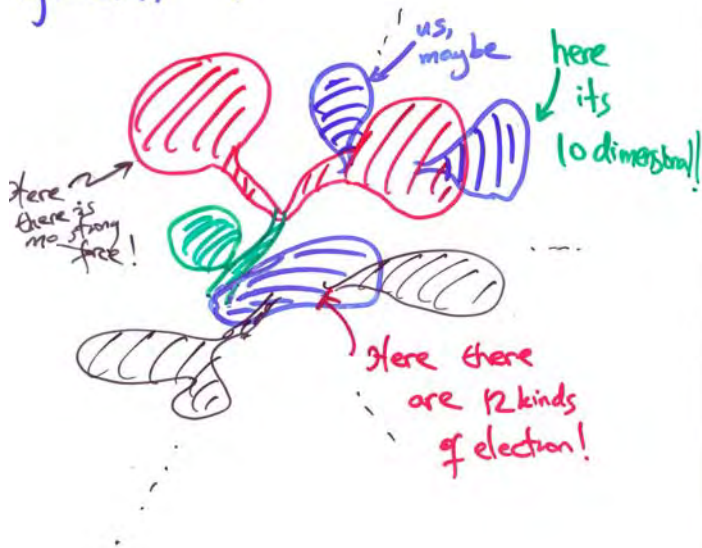
pre '95: zillions ~ millions.

post '95: zillions ~  $10^{1000}$ 's!

All part of same theory,  
but different looking at long  
distances. "String Landscape".

CONTROVERSIAL SUBJECT.

→ The Universe on enormously large scales is an infinite "fractal":



How is our vacuum chosen?

[No sense in asking what  
"fraction" is one or other:  
 $\infty/\infty = \text{anything!}$ ]

• We are clearly missing  
something **BIG** here:  
understanding QM + Cosmology  
crucial to make progress.

EMERGENT TIME ?  
Active Area of Current Research

EXPERIMENTAL  
TESTS/  
HELP?

# Taming the Vacuum

Even vacuum has energy!  
[Again: uncertainty principle]



bigger fluct  
at smaller  
distances

Estimate:

$$\Delta \sim \frac{\text{Energy}}{\text{Volume}} \sim \left( \frac{\text{Planck Energy}}{\text{Planck Vol.}} \right)$$

But energy curves spacetime!  
curvature  $\sim 10^{-33}$  cm!

Universe would double in size every  
 $10^{-43}$  s!



In fact, biggest experimental  
discovery of last 20 yrs - the  
universe is accelerating, but  
doubles in size every  $10^{10}$  yrs!

$$\Delta_{\text{observed}} \sim 10^{-120} \Delta_{\text{estimate}}$$

Biggest error in history of  
physics.

"Why is Universe Big + Flat???"

What we do:

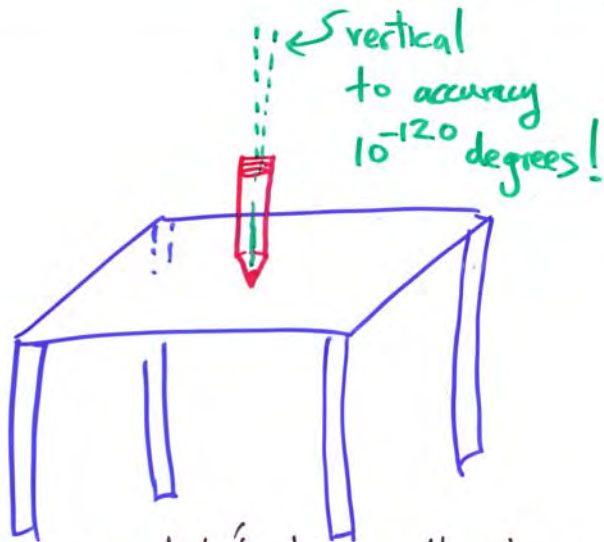
"Fine-tuning"

$$\Lambda_{\text{obs}} = \Lambda_{\text{classical}} + \Lambda_{\text{Quantum}}$$

$-2.649378\dots 52\dots$        $2.649378\dots$  <sup>114 more</sup>  $53\dots$

Differ only in  
121<sup>st</sup> decimal  
place!

LUDICROUS



If this didn't happen, though,  
we wouldn't exist. NOTHING  
WOULD. **EMPTY UNIVERSE.**

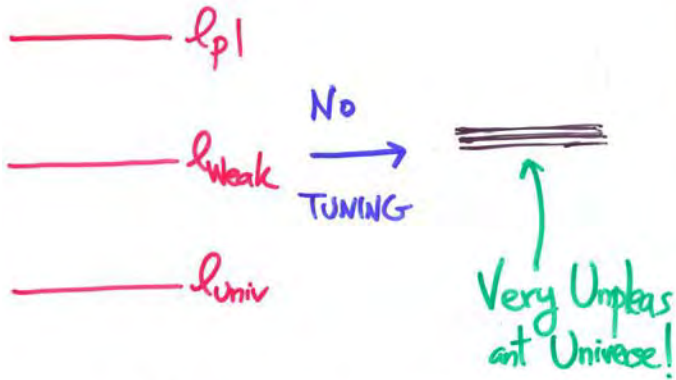
There is a virtually identical  
problem with the origin  
of mass in Standard Model!



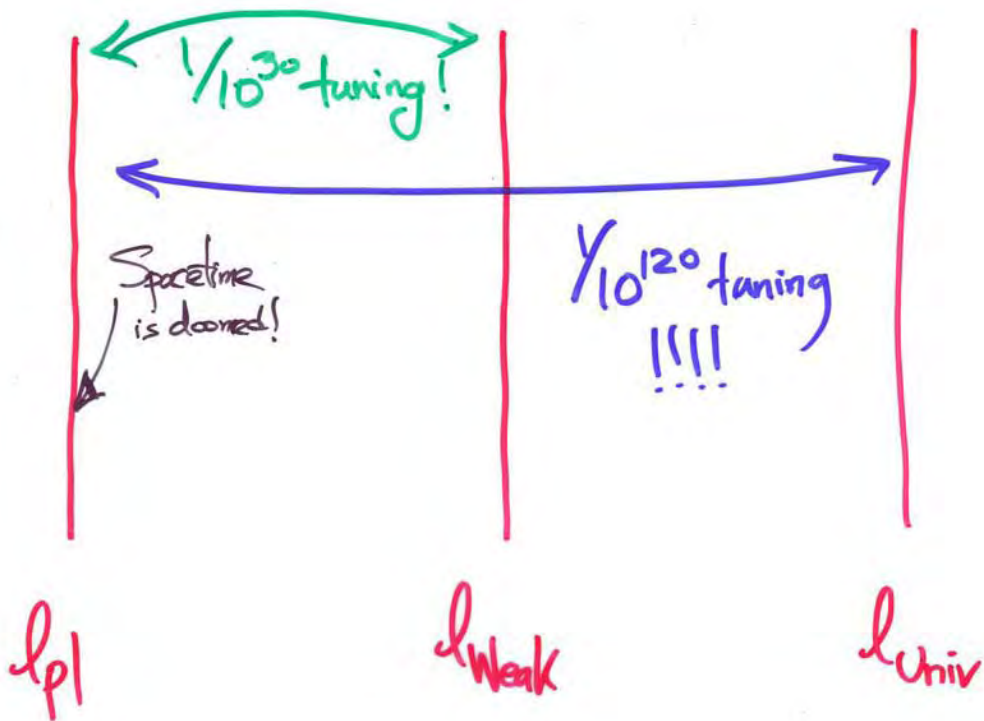
Estimate for  
distance between  
collisions is  $10^{33}$  cm!

Observed  $10^{-17}$  cm value need  
a "tuning" of 1 in  $10^{30}$ !  
[If this didn't happen we wouldn't  
exist].

"Why is Gravity Weak"?



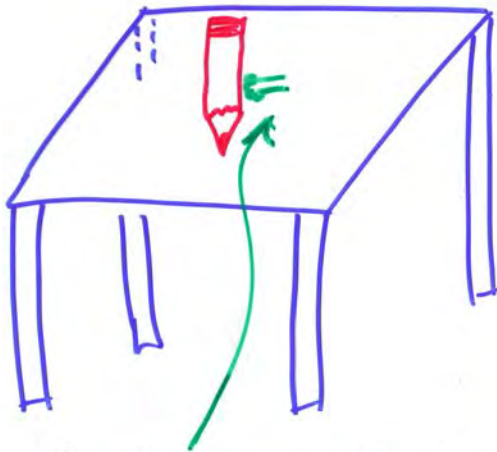
What Controls the  
Violent Fluctuations  
of the Vacuum?



The L.H.C. will definitely ~~might~~ shed light on one of these questions; if we're very lucky, it might illuminate ~~all~~ of them.

Recall L.H.C. will definitely probe the "Higgs" - if something tames the Higgs's violent vacuum fluctuations - L.H.C. must see it, revealing a new principle of Nature.

What might it be?




New Extensions of Spacetime  
can tame these fluctuations. Again -  
must be seen @ L.H.C.




• Most theoretically appealing  
idea: just as  $QM + SR$   
introduced antiparticles and  
solved classical infinite electron  
energy problem





an extension of relativity,  
incorporating quantum dimensions  
+ known as Supersymmetry,  
further doubles the world  
+ amazingly solves Higgs problem!  
If true: other half of world waiting at LHC!


"spin"  $\frac{1}{2} h$   
  
electron

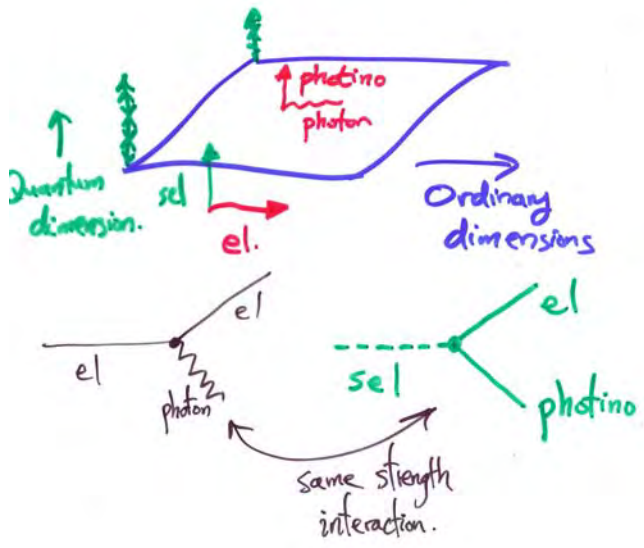
"spin"  $0 \cdot h$   
  
"selection"

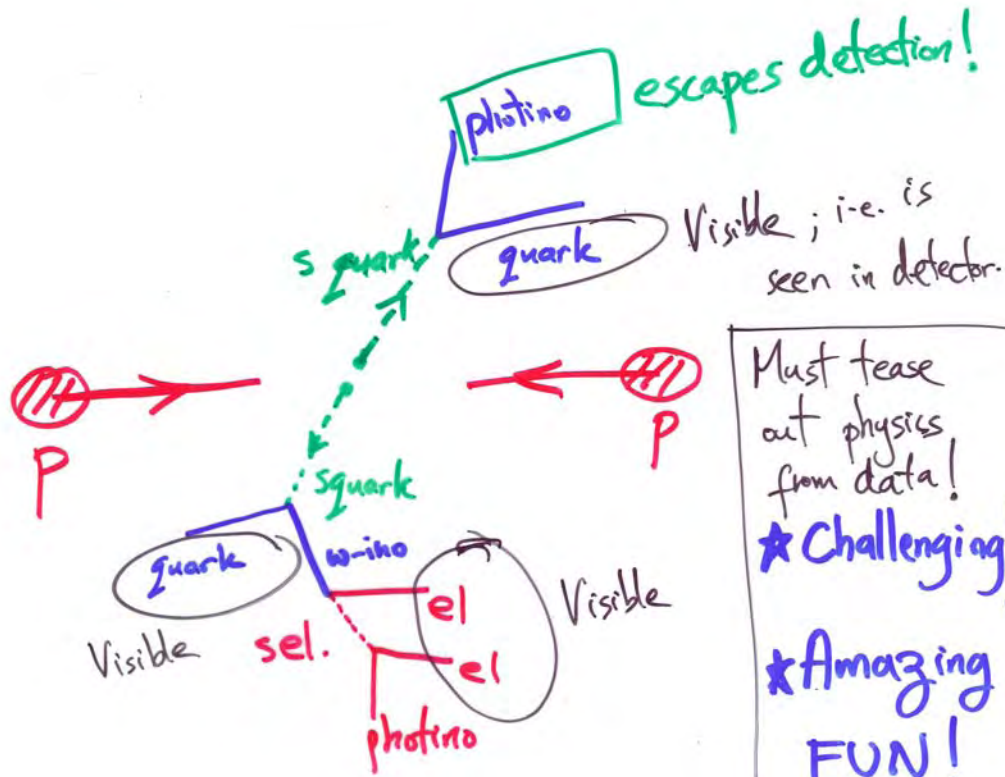
  
photon  
"spin"  $1 h$

  
"photon"  spin  $\frac{1}{2} \cdot h$



  
Cancel, by virtue  
of symmetry between  
them





Must tease  
 out physics  
 from data!  
 ★ Challenging!  
 ★ Amazing  
 FUN!

Another possibility: Strings + Quantum Gravity at the L.H.C. (!!)

$10^{-17}$  cm



Higgs + everything else.



3-d Membrane floating in extra dimensions

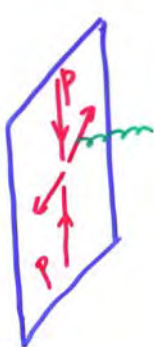
$10^{-17}$  cm

gravity lives everywhere

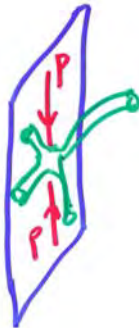
Extra dim can also be big: from  $10^{-17}$  cm - 1 millimeter!

... If this Scenario  
is realized in Nature ...

- L.H.C. is a Quantum Gravity  
Machine



losing  
energy  
into  
extra d



Making  
Strings



Making  
Black Holes

All with distinctive signatures.

Another explanation for  
tunings: enormous diversity  
of environments



Just night  
distance!

Not surprising given  
Billions of Galaxies



we are  
here

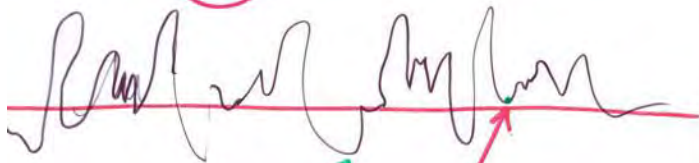
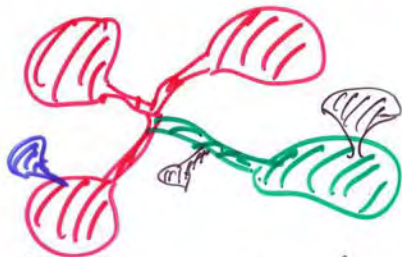


$$\frac{V_{\text{Earth}}}{V_{\text{Univ}}} \approx \frac{1}{10^{60}}!$$

Again obvious -  
we can't live  
anywhere else!

Could we be a tiny part  
of a vast multiverse?

More  
than  
 $10^{1000}$   
worlds!

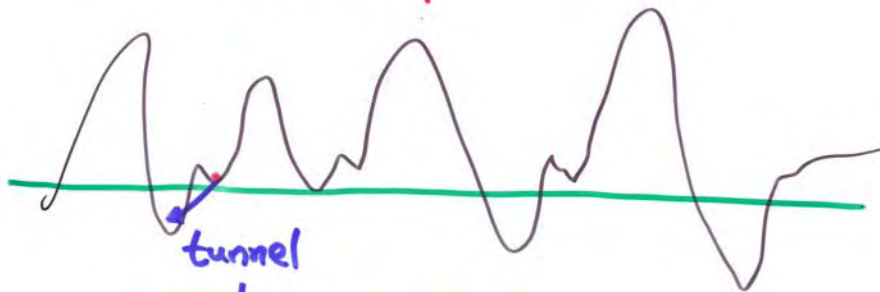


Univ. Everywhere  
Lethal+EMPTY  
except  
...

here, accidentally,  
 $\Lambda_{\text{classic}}$ ,  $\Lambda_{\text{quantum}}$   
cancel accurately  
enough so Univ  
not EMPTY



Our "Vacuum" will have  
a catastrophic end



tunnel  
into

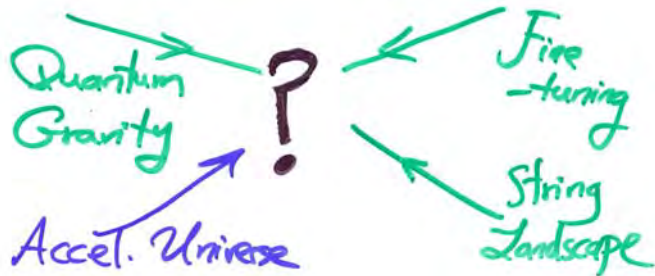
a **BIG CRUNCH**  
in our future

If this picture is true,  
modern Copernican Revolution -  
biggest discovery of our time.

Conceptual problem: can't (yet)  
"see" other universes - how  
can we know they are there?

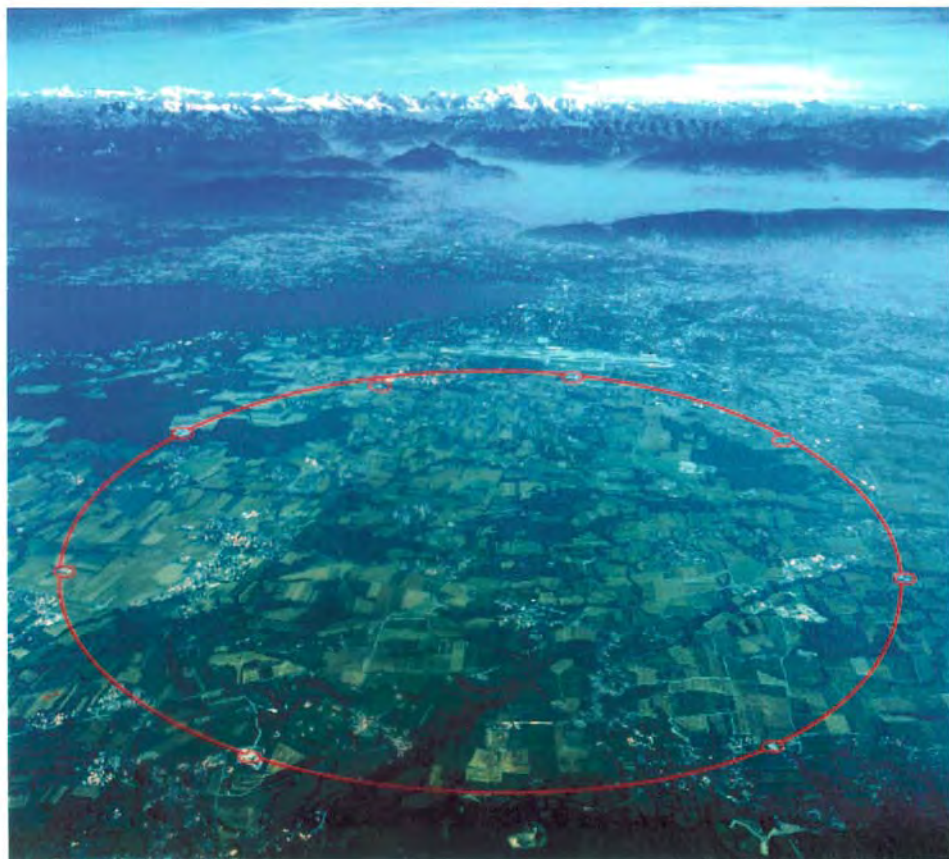
- Could the L.H.C. weigh in on this? **YES!**
  - NOTHING beyond usual Higgs, or, in some well-motivated theories
  - The detection of peculiarly long-lived particles.

We have seen the modern ideas of theoretical physics, on a collision course with each other as well as experiments:



The last time tensions  
about fundamental ideas  
was so high was the  
eve of the twin  
revolutions of relativity +  
Quantum Mechanics. The  
Stakes are very high.

We all await the L.H.C.  
— and its first glimpse into really  
new territory in 30 yrs — with  
bated breath. Will we find new  
symmetries of spacetime? Quantum Gravity?  
Or to the contrary, will we be more Multiversed?



# STAY TUNED

We should have  
something solid to  
say by 2010.